

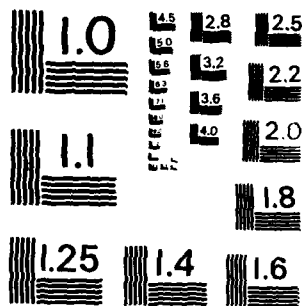
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REPORT

MRL-R-875

RESULTS FROM AN EXPERIMENTAL RAILGUN SYSTEM : ERGS-1A

Y.C. Thio, G.A. Clark and A.J. Bedford

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ABSTRACT

One phase of the Materials Research Laboratories (MRL) Experimental Rail-gun System (ERGS-1) program is for experimentation in the energy range 50 to 500 kJ. The first, and highly successful, ERGS-1 experiment was conducted in September 1981 using a barrel segment 200 mm in length. Comparison of experimental results with the theory developed by Thio yielded good agreement, particularly the values for capacitor voltage, current through the rails, plasma voltage and muzzle velocity of the projectile.

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RESULTS FROM AN EXPERIMENTAL RAILGUN SYSTEM: ERGS-1A

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KEYWORDS

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Electric Propulsion	Capacitor Voltage	
	Rail Current	
	Plasma Voltage	

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ABSTRACT

One phase of the Materials Research Laboratories (MRL) Experimental Rail-Gun System (ERGS-1) program is for experimentation in the energy range 50 to 500 kJ. The first, and highly successful, ERGS-1 experiment was conducted in September 1981 using a barrel segment 200 mm in length. Comparison of experimental results with the theory developed by Thio yielded good agreement, particularly the values for capacitor voltage, current through the rails, plasma voltage and muzzle velocity of the projectile.

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RESULTS FROM AN EXPERIMENTAL RAILGUN SYSTEM : ERGS 1A

1. INTRODUCTION

Steady-state analyses of the behaviour of the plasma armature in a rail-type electromagnetic launcher were provided by McNab [1] and Powell and Batteh [2]. Almost concurrently, Thio [3,4] formulated a fairly comprehensive dynamic theory for modelling the performance of plasma-armature rail launchers. Experiments have been designed to check the various aspects of this theory and to indicate the direction for further refinement of the theory. One phase of these experiments uses our so called ERGS-1A device, (Experimental Railgun System-1) [3]. The ERGS-1 program is aimed at covering the energy range between 50 kJ and 500 kJ.

The present report communicates the first successfully completed experiment of ERGS-1 conducted on September 17th, 1981, and compares the results with theory. In Section 2, a brief resume of the theory is given while the experimental set-up is described in Section 3. The results, theoretical and experimental, are presented and discussed in Section 4.

2. RESUME OF THEORY

The theory is aimed at solving for the forces on the projectile and the voltage drop across the plasma armature, given the rail-gun circuit. A principal feature of the simulation code is to incorporate the circuit equations for the whole system together with known equations for a plasma and to simultaneously solve these equations to satisfy the rail-gun model. A time profile is used to provide the dynamic model for the plasma; this is different from the position profile approach of Powell and Batteh [2]. To calculate conductivity of the plasma the theories of Schmidt and Spitzer are used. It is believed that neither of these is adequate since they do not take into account the presence of a magnetic field and it is expected that comparisons of experimental results with those predicted from the theory will lead to refined expressions for plasma conductivity in a rail-gun.

The system is divided into 4 elements : the power source, the bus-bars, the rails and the plasma. For each element, a model calculates the electrical impedance and these are combined into an equation governing the electrical circuit. The equation of motion of the projectile completes the system of equations which may be integrated numerically. The outcome is PARA, a computer simulation code for the operation of plasma armature rail accelerators.

Approximate models for power source, bus-bars and rails exist and were found adequate for the present purpose. The element which required substantial modelling development was the plasma.

Figure 1 shows the overall structure of the plasma model used. Starting with the equation of magneto-hydrodynamics and the equation of state, the pressure distribution within the plasma can be calculated if the temperature is known. The temperature is calculated from the equation of radiative heat transfer. Knowing the temperature, the degree of ionization can be determined. The three aspects, pressure within the plasma, its temperature and degree of ionization, then specify the dynamical state of the plasma.

From this, the volume of the plasma can be determined. Combined with the degree of ionization, the average electron density can be found. From the temperature and the electron density, the conductivity of the plasma can be determined. Knowing the conductivity and the volume allows the electrical impedance of the plasma to be specified.

A second line of calculation which makes use of a knowledge of the gas pressure leads to the determination of the force on the projectile. Two cases need to be considered. The first is the case in which the plasma is completely confined by magnetic pressure and stands clear of the breech. In this case the forces acting on the plasma are purely electro-magnetic. The second is the case in which the plasma is in contact with the breech. The breech adds a secondary pressure to the plasma as the plasma expands thermally; very much like the explosive effect of a conventional gun. Both the electro-magnetic and explosive effects are incorporated in our theory.

3. EXPERIMENTAL ARRANGEMENT

The experimental device described in this report is commonly known as a plasma armature rail-gun. A polycarbonate projectile rests near the breech end of the rails and on the back of this projectile is mounted a piece of 50 μ m aluminium foil. This foil forms a short circuit between the rails.

Once power is supplied to the rail-gun the foil vapourises and creates a plasma armature behind the projectile. The electromagnetic force acts on the plasma accelerating it along the rail-gun bore and forces the projectile ahead of it.

This has become a conventional way of firing plasma driven rail-guns powered by a capacitor-inductor circuit. The system can be modelled and is

providing important knowledge on rail-guns. However, there are penalties such as severe rail-damage in starting projectiles from rest and although the system is preferred for many experiments it is not expected that it will provide an optimum solution for a future working system.

3.1 Architecture of ERGS-1

The electrical circuit used is schematically shown in Figure 2. A bank of 34 BICC capacitors connected in parallel, having a total capacitance of 2611 μF provided the prime energy source. The bank was connected via a pair of parallel transmission plates to an inductor of 6.5 μH . A triggered spark gap was used as the main switch. The capacitor bank was equipped with a crow-bar switch which consisted of a fuze wire sitting in a gap between two electrodes each of which was connected to a terminal of the capacitor bank (Figure 3). Between each end of the fuze wire and a terminal of the capacitor bank was connected a low-current rating diode (LA80). The fuze wire was a 100 millimeter length of 44 Gauge B&S (50 μm) bare copper wire. The desired operation for the crow-bar switch is that the diode should conduct current through the fuze just after the capacitor voltage reverses. The current, though small, is large enough to explode the wire. The resulting plasma causes the gap between the electrodes to break down thus providing the required path for the current to by-pass the capacitor bank. The exploding of the fuze wire breaks the diode circuit and thus protects the diodes from being damaged during the operation.

In both the main spark-gap switch and the crow-bar switch, arc-resistant copper-tungsten (70% Cu, 30% W) infiltrate was used as the material for the electrodes.

For the barrel of ERGS-1, a cylindrical geometry was adopted, as it makes more effective use of the materials in containing the very large bursting stresses involved than, say, rectangular ones. However, it does make extraction of rails after firing rather difficult. The basic design concept was similar to one used by the LASNL-LLNL group [5] but in our case all barrel materials other than the rails were non-conductors. A pair of copper 0.6% cadmium rails were backed by 2 pieces of alumina ceramic and two more pieces set them apart (Figure 4). The assembly was then potted in epoxy reinforced by silica. Finally the barrel was wound with Kevlar fibre in epoxy. Further design details were given by Thio [4]. In this first experiment, a section 200 mm long was used.

To enable future experiments to run under vacuum a plug and socket arrangement was devised to connect the rail-gun to the main bus-bars. An internal wedge applied a high pressure at the junction with the intention of forming a low-resistance joint there. An o-ring completed the vacuum seal.

Arc-transfer electrodes, in the form of D-shape copper blocks, were connected to the rails at the muzzle, one electrode per rail (Figure 4b). The separation between these arc-transfer electrodes was less than the bore of the gun. The intended operation was that, after the projectile had left the bore, the plasma would initiate a breakdown between the electrodes creating a

current path for dissipating any residual electrical energy which remained trapped in the inductance of the circuit. This would help to prevent further damage to the rails by the residual energy.

3.2 Instrumentation

A Rogowski belt was used to measure the current. Its signal was integrated electrically before recording. Voltage probes were placed at the capacitor terminals, at the breech and at the muzzle. Digital transient recorders (3 Biomation Model 805 and 1 Datalab Model DL905) were used for recording the electrical measurements. Out-of-bore velocity was measured with a pair of break-wire screens placed 400 mm apart. Though internal holes were drilled into the barrel to provide access to the bore for a fibre-optics in-bore diagnostic system, they were not used in this first experiment. A FASTAX camera (~ 15,000 frames per sec) was used to capture the motion of the projectile on exit from the gun.

To avoid undesirable earth loops to the measuring devices, no earthing was used during the experiment. After charging, the capacitor bank was disconnected from the earth of the charging unit by a pneumatic switch. All instruments were electrically isolated from each other by using mains isolation transformers or battery operated inverters as their power sources.

External triggering of transient recorders was provided by photo-coupler amplifiers (again for electrical isolation) which themselves were triggered by a pick-up coil positioned in the inductor of the rail gun. The main spark gap switch trigger unit was also triggered via a fibre-optic cable to ensure complete electrical isolation.

Although considerable attention was given to instrumentation requirements in this early experiment, only voltage/current measurements were attempted from which a very basic idea of plasma behaviour could be estimated. The properties and behaviour of the plasma form one of the most important areas for study in this type of rail-gun and in future experiments much more extensive measurements are envisaged.

4. RESULTS AND DISCUSSION

The projectile mass was 0.36 g and the aluminium foil mass was 0.01 g. Overall system efficiency was 0.4%, this being calculated from the total electrical energy expended in the firing and the kinetic energy achieved by the projectile. A very low value was expected because of such factors as starting the acceleration from rest, (plasma driven rail-guns become more efficient as velocity increases) and because a short barrel length meant that only a small proportion of the total energy available was used to accelerate the projectile. Methods of increasing the efficiency of rail-guns is one of the most important problem areas receiving attention in most electromagnetic launch programs, including that at NRL.

Figure 5 shows the capacitor voltage versus time. The solid curve was calculated theoretically, whereas the experimental values are indicated by the points. The measured potential on the capacitor falls from its charged voltage of 6.94 kV sinusoidally, in very much the same way as an under-damped RLC circuit. It crosses zero at (218 ± 9) microseconds and overshoots by (1.0 ± 0.2) kV before a damped oscillation sets in. We interpret this instant as the onset of a plasma discharge across the crow-bar gap. The damped oscillation of the potential is characteristic of the presence of inductance and resistance in the circuit comprising the capacitor bank, the transmission plates, and the spark gap forming the crow-bar switch. The theoretical curve follows the experimental values closely, up to when the voltage crosses zero after which the theoretical curve ceases to have any meaning as the theoretical potential on the capacitor is held at a constant value of -500 V.

Figure 6 shows the time-profile of the current flowing in the rails as measured and theoretically calculated. The measured current rises in a sinusoidal manner to a value of 124 ± 15 kA in 195 ± 10 us. A kink is clearly visible in the analogue display (not shown) of the measured current record at about the same time as the crow-bar gap appears to be turned on as deduced from the capacitor voltage record. After this time, the current can be seen to fall gradually as in an inductively driven LR circuit. Again the theoretical curve follows closely the experimental values up to the instant of exit of the projectile.

A more significant test of the theory is the comparison between the calculated values of the voltage across the plasma and the measured values. Figure 7 shows this comparison.

Experimentally, the plasma voltage was measured as the voltage drop appearing across the rails at the muzzle. The measured value rises sharply to a value of 351 ± 30 V in 11 ± 4 us after closing the main switch (This is not the same as the origin of time $t = 0$ used in Figure 7. See later). This time lapse would include the time required to heat the aluminium foil up to its vaporisation temperature, the initial abrupt expansion of the aluminium vapour, the formation of a plasma out of this vapour and/or adjacent materials including gases in the barrel. The voltage, however, falls rapidly; 120 us after the switch closed it dropped to a value of 180 ± 30 V; then it rose again gradually to another peak value of 225 ± 30 V.

Two cases of the theoretical results are shown. One uses Schmidt's [6] theory for plasma resistivity; the other is based on Spitzer's theory [7]. The origin of time ($t = 0$) is assigned to the instant when the aluminium foil has been heated to its vaporisation temperature and a plasma consisting of aluminium vapour confined by the projectile and the breech or the magnetic pressure has been formed. The time base for the experimental results is chosen so that the initial experimentally recorded spike in the muzzle voltage is made to occur at the same instant as a similar spike in the theoretical results. This instant corresponds to $t = 4$ us. It appears therefore that 7 ± 4 us was needed to vaporise the aluminium foil in the experiment. Experimentally, the occurrence of the spike may be due to one or a combination of several effects: before the foil vaporises, its resistance increases with temperature, and with increasing current should give rise to increasing voltage drop across it. After the foil vaporises, a plasma is formed;

initially the plasma is relatively cold and has a high resistance. As it is heated, its resistance decreases. This does not necessarily lead to a decrease in the voltage drop across it as the current is increasing at the same time. However, eventually the decrease in the plasma resistance overcompensates for the rise in current leading to a fall in the voltage across it. The theoretical calculations, however, take as the starting point the instant after the aluminium foil has vaporised and a plasma with uniform temperature has been formed. After the initial spike, the plasma resistance stabilises to a certain degree and the voltage across it varies in much the same way as the current though not exactly in phase with it.

The two theoretical curves display very similar temporal characteristics as the experimental results: a spike, a rapid fall, a gradual rise to a maximum at $t = 210$ us, falling again afterwards. Even though neither the Schmidt nor the Spitzer theories take a B-field into account, for most of the time the experimental values are bounded by the theoretical curves calculated using Schmidt's and Spitzer's expressions for the plasma resistivity.

The experimental values appear to lie closer to the curve using Schmidt's expression (for most part, within 10%) than the one based on Spitzer's expression (where deviation up to 30% occurs). We do not, however suggest that Schmidt's expression is more appropriate in the present application. Firstly, the quantitative effects of some of the assumptions made in the theory, such as a 1-D model, are not entirely obvious. Secondly, the theoretical results are sensitive to the mass assumed for the plasma. The results shown in Figure 7 are calculated with the mass of the plasma assumed equal to the initial mass of the aluminium foil used in the experiment; it was 50 μ m thick and measured 6 mm x 11 mm. A more thorough examination of these aspects is proceeding.

Another test of the theory is the velocity of the projectile. Figure 8 shows the velocity-position profile for the projectile as calculated by PARA. At 200 mm which is the position of the muzzle, the expected velocity of the projectile was 1.3 km/s. The break-wire measurement of the projectile velocity was 1.2 km/s.

To complete the results, we show in Figures 9-13 the time-profile of the total pressure of the plasma just behind the projectile, the plasma temperature, the degree of ionization, the length of the plasma and the magnetic flux density just behind the plasma as calculated by PARA for the experiment. In each of these figures, two curves are shown: one corresponds to the use of Schmidt's theory for plasma resistivity and is indicated as curve (1), the other curve is based on Spitzer's theory and is indicated as curve (2). In the following description of the results, we shall refer primarily to the results based on curve (1). In cases where the results of curve (2) differ significantly, the corresponding results are enclosed within brackets. The total pressure on the rails and the ceramic was expected to attain a peak value of 55 MPa, very much below the design pressure of 300 MPa. The highest temperature reached should be about 26000°K in the plasma which was expected to be strongly ionized. The plasma should have been in contact with the breech for 128 us by which time it should be 48 mm (42 mm) long, and then it should be confined by magnetic pressure and should

have a length varying between 40 mm (36 mm) and 50 mm (42 mm). The magnetic field generated in the region between the rails was expected to reach a value of 11.7 Tesla at peak current. Despite the variation in temperature and the consequent variation of plasma resistivity, the resistance of the plasma should be fairly constant with a value of $2.0 \text{ m}\Omega$ ($1.2 \text{ m}\Omega$) when the current is nearly maximum.

As an integral part of the theoretical calculations, thermalization time, Debye length, cyclotron frequency and collision frequency for particles in the plasma were calculated. For the most part, thermalization time for all the particles was less than 1 ns, very much smaller than the time-scale of events we were interested in. This validates the assumption of a uniform temperature for all species of plasma particles and the use of Spitzer's equation for calculating the degree of ionization. Similarly, the Debye length which was very much less than a micrometer throughout the period of interest was much less than the system dimensions, thus an MHD approach was appropriate. The cyclotron frequency, which is a measure of the influence of the magnetic field on the motion of the electrons, had a maximum of $2.1 \times 10^{10} \text{ Hz}$ whereas the maximum collision frequency was slightly beyond $8.3 \times 10^{13} \text{ Hz}$. Under these conditions, the application of Spitzer's or Schmidt's expressions for plasma resistivity was reasonable. Overall, these indicators do show that the theoretical calculations were indeed pursued within the bounds of validity of the assumptions made, i.e. the theoretical results were at least self-consistent.

5. RAIL DAMAGE

After the firing, each rail was extracted from the supporting barrel structure and surface and metallurgical examinations were conducted. Figure 14 shows the surfaces of these rails.

A black deposit left on the rail surfaces after firing was easily washed off to reveal a globular appearance indicative of melting and resolidification. More melting had occurred near shot start where the resultant surface was quite rough. Towards the muzzle end of the rails the damage appeared less severe and was characterised by a fine chevron or rippled appearance.

Cross sections under an optical microscope showed that the surface layer had been molten; and extending from this layer were both transgranular and intergranular cracks (Figure 15).

Scanning electron microscopy showed the severity of surface melting and the differences in the damage along the rails. Figure 16 shows the cracks on the surface of the rails towards the breech as well as the characteristics of a molten and resolidified surface. Figure 17 is a higher magnification micrograph showing a crack extending down from the rail surface.

Towards the muzzle end of the rails the surface damage was less severe and Figure 18 shows the finer ripple like appearance.

The damage observed, as expected, bore similarities to severe arc damage seen in electrical switching. However, the magnitude of the damage in the present case is very large due to the severe conditions during plasma acceleration in the rail-gun. Where small amounts of damage have been observed on test rails the more classical arc spots are observed to be similar to those reported by workers investigating conventional arc damage.

The surface of the rails obviously melts and again, as expected, melting is more extensive nearer the breech end where the dwell time of the plasma is greatest. The short times in which this surface melting occurs and the rapid quenching, due to the bulk of the rails, combined with high surface pressures is probably the cause of the cracks in the rail material.

Nearer the muzzle end, where the projectile is travelling near 1 km/s, there is less arc damage and this is in agreement with other observations or impressions [8]. There have been suggestions that rail damage may be greatly decreased if a projectile is injected into a plasma driven rail-gun at velocities above 500 m/s so that the high initial damage is eliminated. Other means of reducing rail damage in these devices may involve plating of rails with arc resistant materials, or of using composite rails where the breach area has an arc resisting section connected to the main rail sections of the rest of the barrel.

6. CONCLUSIONS AND RECOMMENDATIONS

The first firing of the MRL ERGS-1 program was highly successful. A barrel segment of 200 mm length was used and a 0.36 g projectile was accelerated to 1.2 km/s. Comparisons of measured values, including capacitor voltage, current through the rails, plasma voltage and muzzle velocity of the projectile, with calculated values from the simulation code developed by Thio were generally within 10% of each other.

The results of this experiment indicate that our theoretical and experimental concepts are very promising and a series of experiments using a longer barrel segment is underway to provide much more experimental information from which theory modifications can be developed.

No new problem areas have been revealed by this experiment. If models are to be improved for plasma driven rail-guns serious attention has to be given to the plasma nature and behaviour. Plasma diagnostics will be needed to plot temperature profiles and their variations with time, plasma length and voltage drops will be required as well as plasma composition. Those laboratories like MRL which are concentrating on the physics of rail guns will be concentrating on these problems as their experimental devices and instrumentation are developed to the stage of routine test firings.

Rail damage remains as an area needing much investigation. Two approaches are being taken; one is to attempt to minimise rail damage by materials selection. This will include plating rail surfaces with arc resistant material, rails made of more than one material and simple rails made from metals other than copper. The other approach is to design rail guns which minimise rail damage and included in this area will be cooled rails and injected projectiles.

7. ACKNOWLEDGEMENTS

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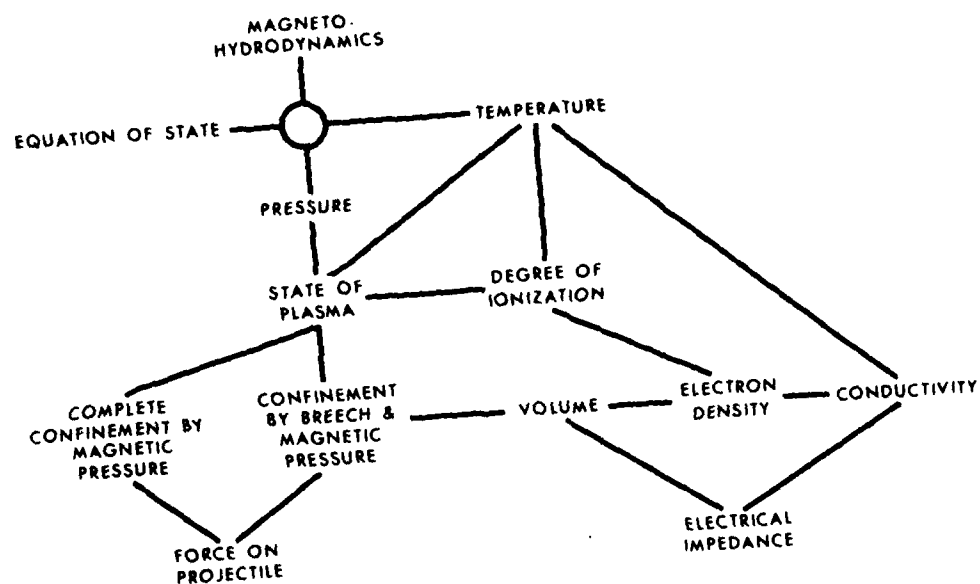


FIGURE 1. Structure of the Theoretical Model of the Plasma.

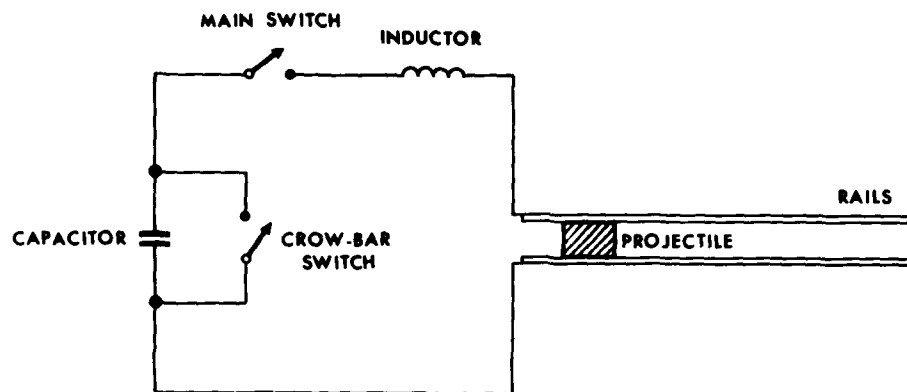


FIGURE 2. Electrical circuit for ERGS-1A experiments.

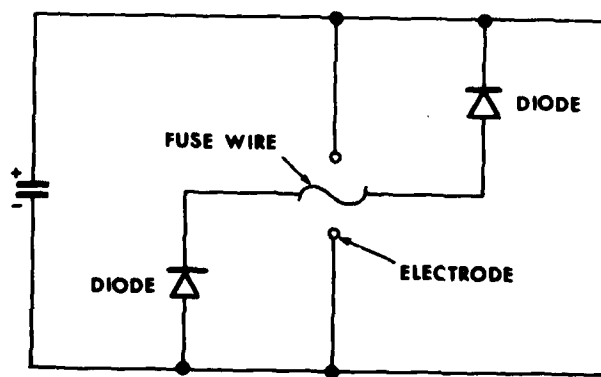


FIGURE 3. Crowbar switch arrangement.

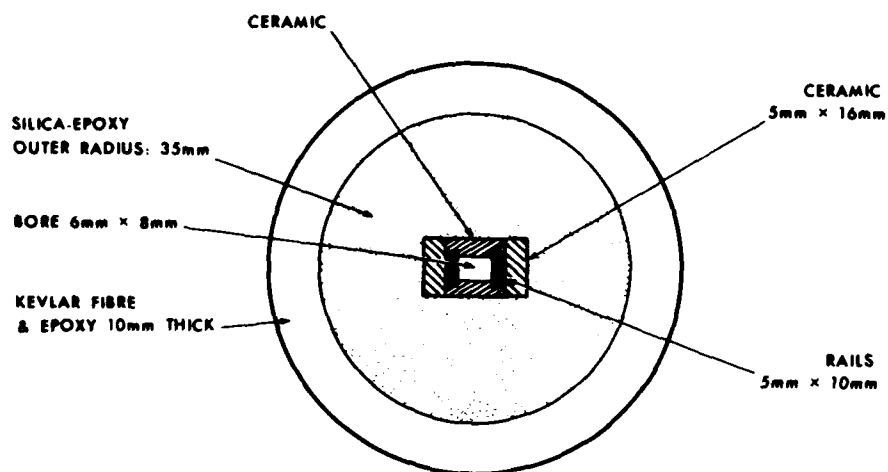


FIGURE 4a. Schematic drawing of cross-section of ERG-1A.

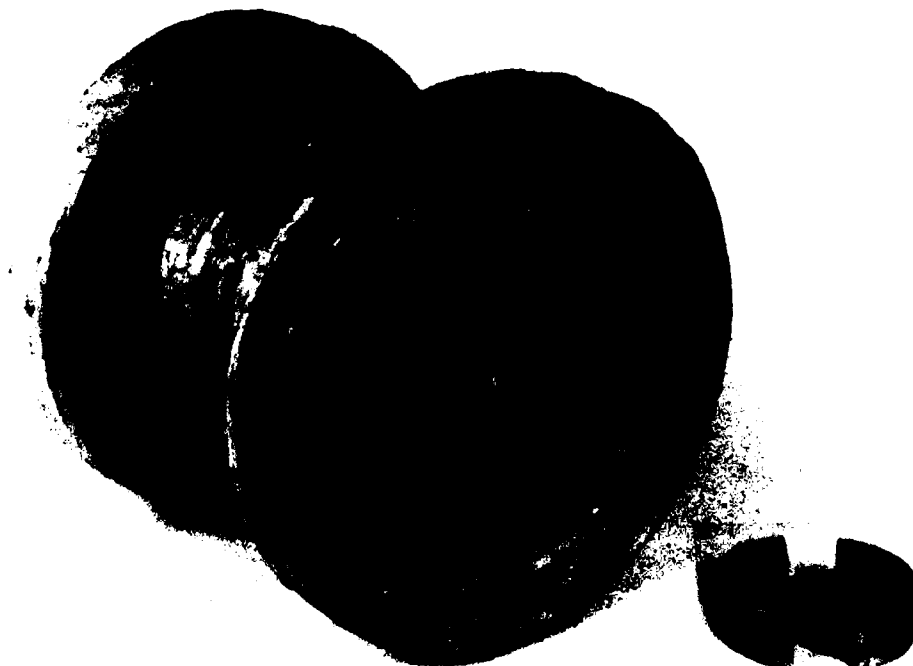


FIGURE 4b. Photograph of ERGS-1A barrel. Shows also the arc transfer electrodes.

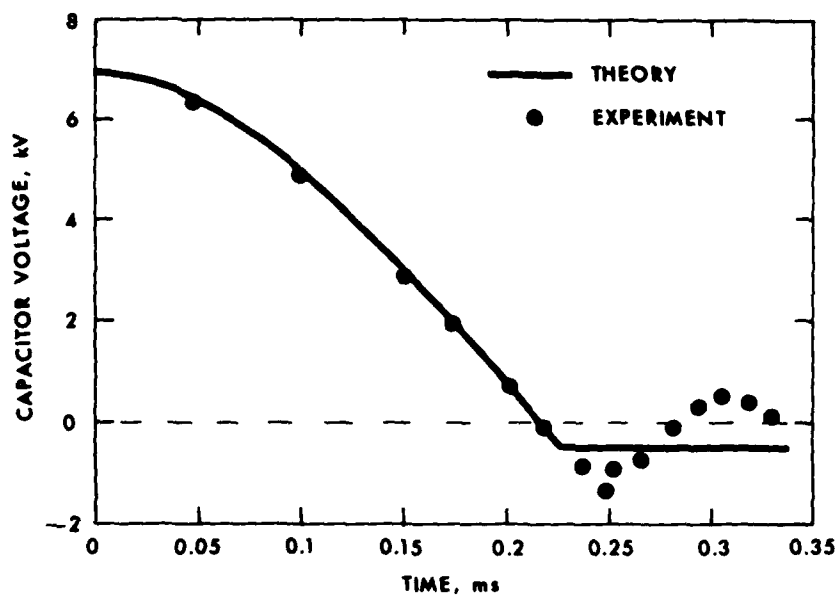


FIGURE 5. Capacitor Voltage Vs Time.

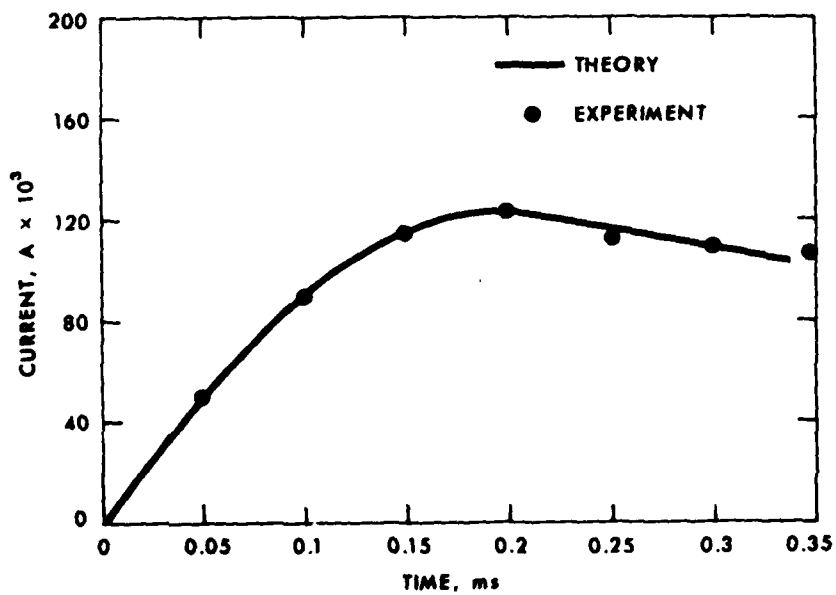


FIGURE 6. Current Vs time.

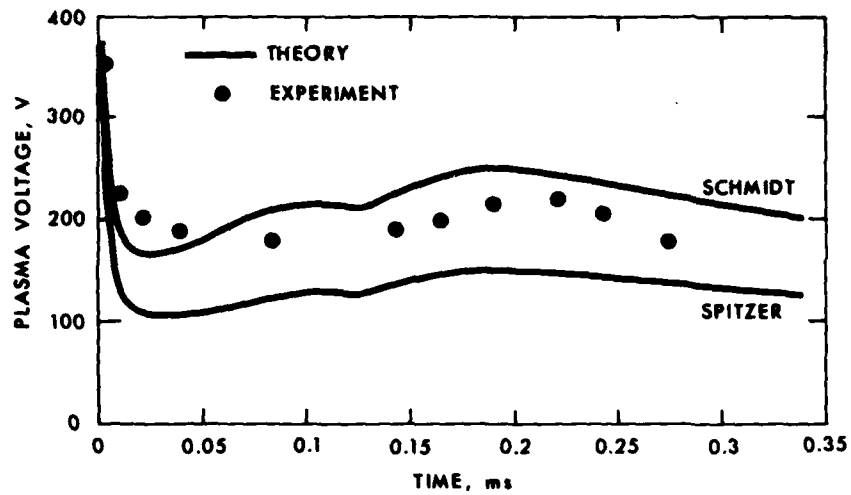


FIGURE 7. Plasma Voltage Vs Time.

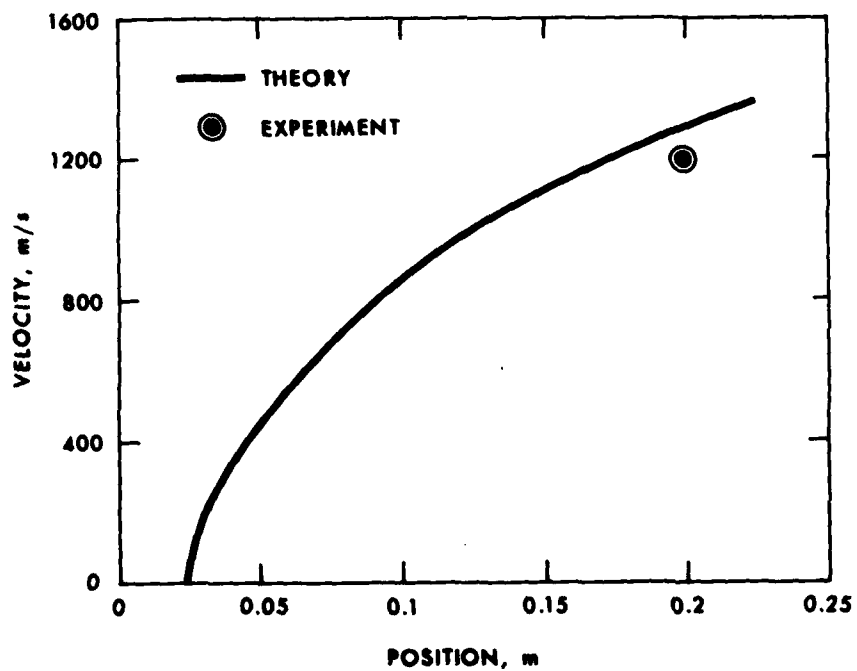


FIGURE 8. Velocity Vs Position.

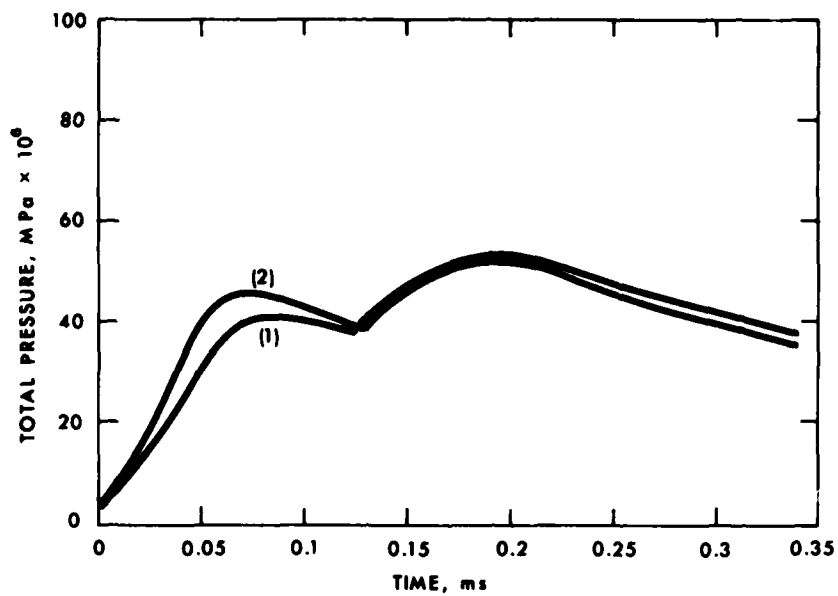


FIGURE 9. Pressure at back of projectile.

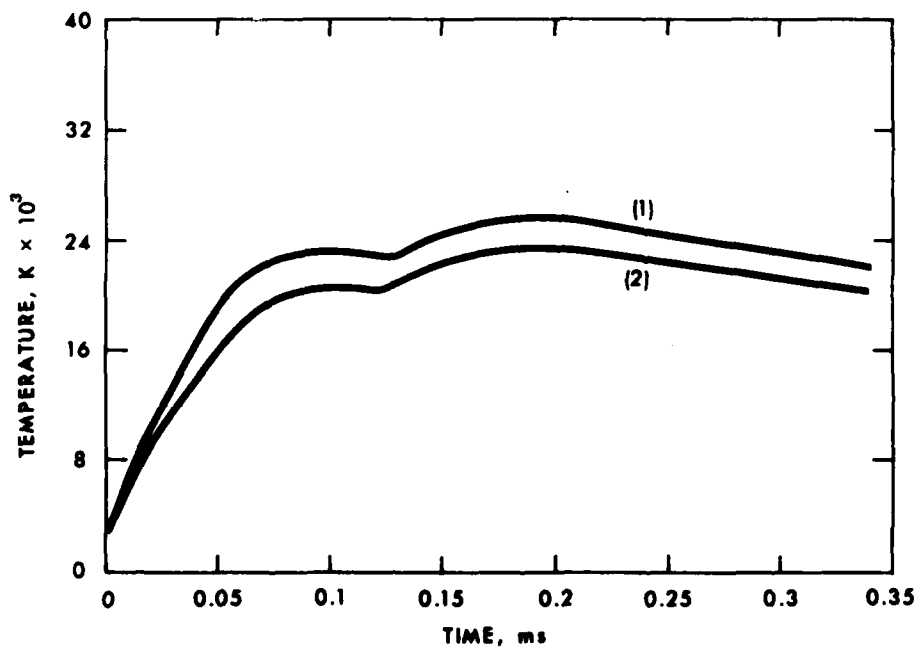


FIGURE 10. Plasma Temperature.

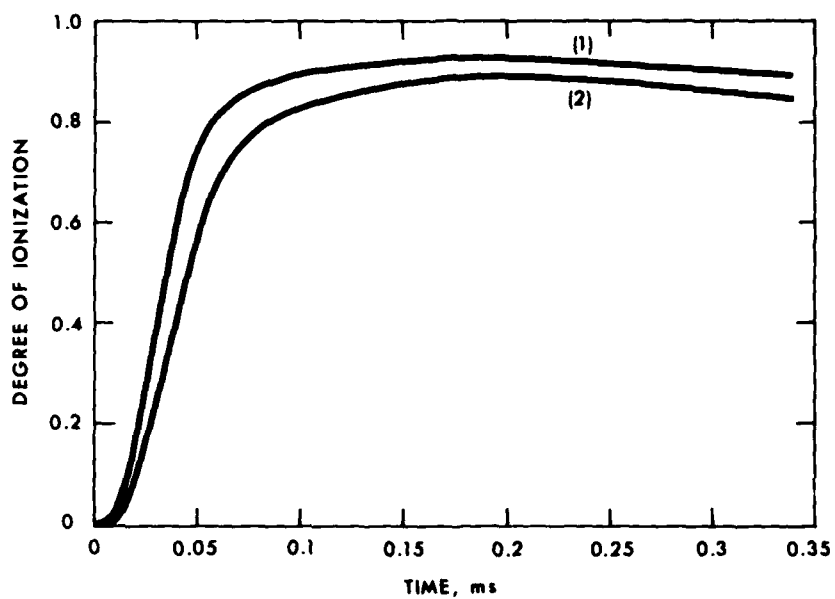


FIGURE 11. Degree of Ionization of Plasma.

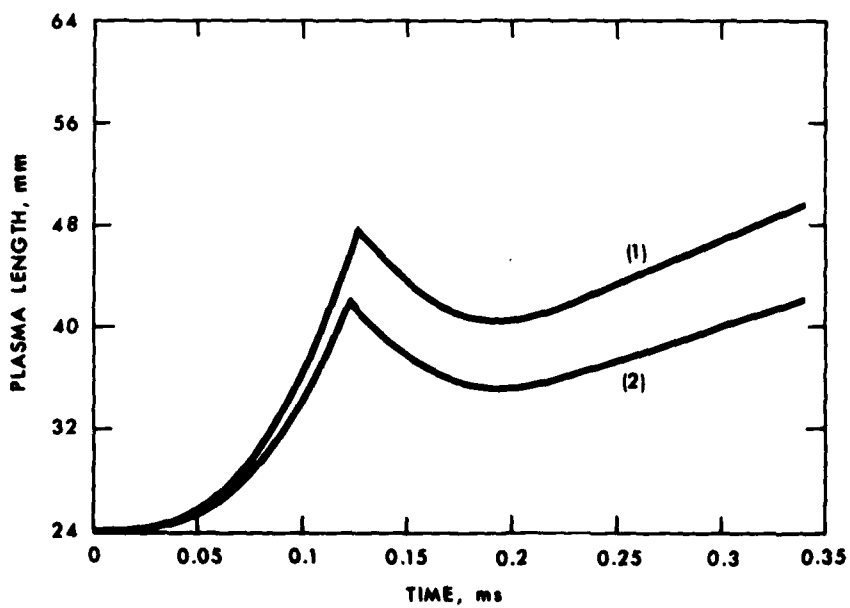


FIGURE 12. Length of Plasma.

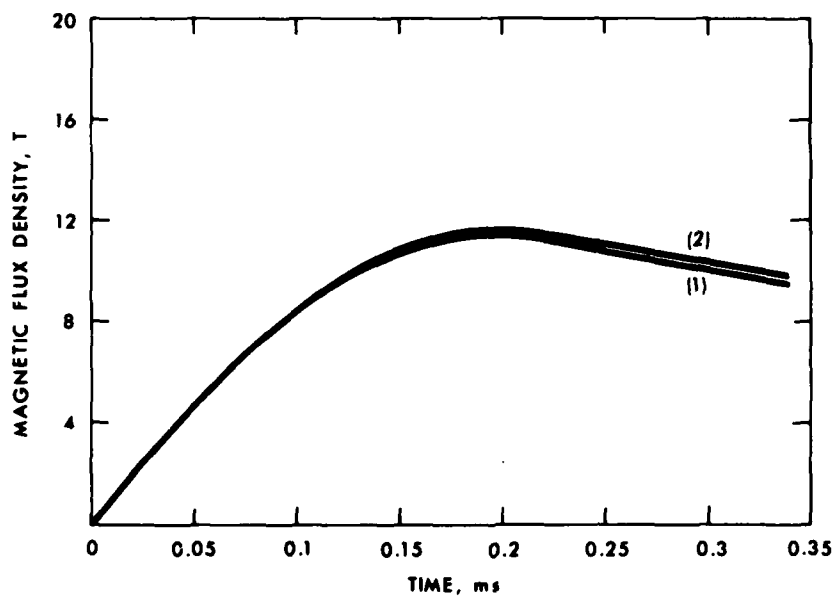


FIGURE 13. Magnetic Flux Density.



FIGURE 14. Surface Appearance of Rails After Firing.



FIGURE 15. Micrograph of rail cross-section showing resolidified surface and sub-surface cracking. 100 μ m



FIGURE 16. Scanning electron micrograph of a rail surface showing signs of melting and cracking. 100 μ m



FIGURE 17. Scanning electron micrograph of a rail surface showing a crack extending into the rail 20 μ m

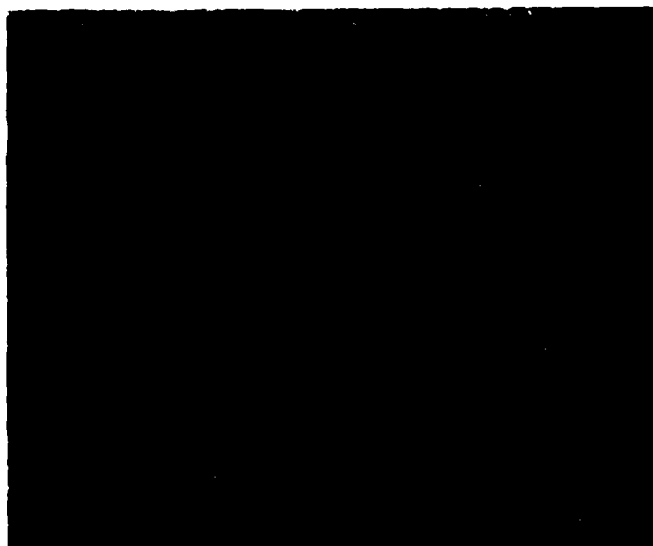


FIGURE 18. Scanning electron micrograph of a rail surface showing ripple like damage. This more uniform damage occurs at some distance from the firing position where the plasma is moving at a high velocity. 1 mm

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